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On the Azimuthal Variation of the Equatorial Plasmapause

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Abstract. Previous results of plasmapause position surveys have been synthesized into a comprehensive description of the plasmapause, taken to represent the boundary between diurnal near-corotation and large-scale circulation streamlines that traverse the entire magnetosphere. The result indicates a plasmapause that has a pronounced bulge in the dusk sector, that rotates sunward and shrinks markedly as geomagnetic activity (and presumably magnetospheric convection) increase. The shape of the plasmapause so determined is significantly different from that associated with the simple superposition of sunward flow and corotation, both in its detailed shape and in its varying orientation. The results imply that the magnetospheric circulation departs from a uniform flow field, having a radial dependence with respect to the Earth that is qualitatively consistent with electrostatic shielding of the convection electric field. Also, the results imply that the inner magnetospheric flow field rotates from duskward to dawnward as its intensity increases.

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he Earth is surrounded at low to mid-latitudes ($1<L<\sim6$) by a toroid of relatively dense ma known as the plasmasphere. This region is distinguished from higher L-shell regions in the circulation of plasma is confined to closed streamlines near the Earth. The diurnal motion e plasma in the plasmasphere is controlled by an electric field induced by the Earth's rotation 1 that the plasma "corotates" with the Earth. At higher L-shells, plasma motion is driven by electric field imposed across the magnetosphere by the interaction of the Earth's magnetic d with the solar wind. A stronger convection electric field moves the boundary between otating and convective regions to lower L-shells, while a weakening of the convection electric ld moves this boundary to larger L-shells [*Nishida*, 1966]. Because of the dynamic nature of solar wind, the convective electric field changes with time, sometimes dramatically.

Plasma flows from the ionosphere out into both of these regions of the magnetosphere. Plasma cumulates in those flux tubes corotating with the Earth and can eventually reach a balance, rresponding to "filled" magnetic flux tubes, where net outflow is quenched. The plasma listribution along corotating flux tubes depends in part upon heating at low and high altitudes and flux tube volume. Plasma densities at higher L-shells, the plasma trough, generally remain low due to continuous convection toward the dayside magnetosphere and possible loss at the agnetopause.

The boundary between these plasma regions is often, but not always, characterized by a pacially sharp density gradient called the plasmapause. The plasmapause is variously defined bservationally to be the location (in L-shell) where the density is between 10 cm^{-3} and 100 cm^{-3}. It is also defined to be the location at which the density falls one or more orders of magnitude over a small range of L-shell (less than 0.5). In addition, the plasmapause region is associated with the transition between cold, isotropic plasma and field-aligned ionospheric outflows. Small scale, complex density structure in the vicinity of the plasmapause reflects the dynamic nature of this inner magnetospheric region. Low density regions are found inside the plasmapause, which may have been emptied due to previous convective forces. High density regions are found on sunward convection paths, which previously may have been confined and filled within the plasmasphere. The azimuthal stagnation of plasma motion near dusk, due to a near balance between convection and corotation may also lead to an accumulation of plasma in that region. In addition to the action of convective electric fields, the velocity interchange mechanism of *Lemaire and Kowalkowski* [1981] may also contribute to plasmapause formation. As a result of gravitational and inertial forces, low density regions spiral toward and high density regions spiral away from the eventual plasmapause, where these forces are balanced. The dynamic nature of the plasmapause formation, can at times result in multiple gradients that meet the definition of plasmapause reviewed above, i.e. multiple plasmapause boundaries [*Horwitz et al.*, 1990].

The diurnal, or azimuthal, shape of the plasmapause in the Earth's magnetic equatorial plane has been studied for many years. The earliest observers reported both dawn-dusk and noon-midnight asymmetries [see review by *Gringauz*,1969]. Subsequent observations present a somewhat confused picture, indicating both symmetric and asymmetric azimuthal plasmapause shapes [*Chappell et al.*, 1970; *Taylor et al.*, 1970; *Brace and Theis*, 1974; *Gallagher et al.*, 1988; *Carpenter et al.*, 1991]. The dawn-dusk asymmetry is characterized by an extension of the evening plasmapause to greater equatorial distances than at dawn. This bulge in the plasmapause shape has been observed to shift sunward and antisunward with increasing and decreasing geomagnetic activity, respectively [*Carpenter*, 1970; *Higel and Wu*, 1984; *Moldwin et al.*, 1993].

The observation of an apparent bulge in the evening plasmapause was initially given support by *Nishida* [1966], where corotational and convection electric fields were superimposed to derive the **ExB** motions of zero energy ions in the equatorial plane. This simple picture of azimuthal ion motion suggested that the canceling of corotational and convective electric fields at dusk would result in a "tear-drop" like extension of the diurnally closed trajectories of plasmaspheric ions. Subsequent study of the penetration of solar wind impressed electric fields into the magnetosphere and the influence of such effects as finite ionospheric conductivity [*Wolf*, 1970], dipole tilt [Quegan et al., 1986; also discussed in *Wolf et al.*, 1986], and interplanetary magnetic field [*Doe et al.*, 1992] have lead to a more complex picture of inner magnetospheric plasma distribution with local time.

The steady state azimuthal profile of the plasmapause and its response to changing geophysical conditions remain an observational enigma. Elliptically orbiting spacecraft passing through the plasmasphere reveal a spectrum of observed L-shell profiles [e.g., *Horwitz et al.*, 1990], which are separately insufficient to characterize the azimuthal structure. Equatorial, geosynchronous orbiting spacecraft azimuthally sample the radially-extended plasmasphere, but it remains difficult to differentiate between azimuthal and radial structures associated with a time-varying plasmasphere [e.g., *Moldwin et al.*, 1993]. Campaigns involving multiple, coincident observations of the plasmapause at varying local times offer the potential of developing snap-shots of radial and azimuthal density structures in the outer plasmasphere, but only for event times and corresponding geophysical conditions. The recent study by *Carpenter et al.*, [1992] does a very good job of discerning plasmaspheric structure in the bulge region for a specific event, but is unable to differentiate between an isolated high density feature separated from the plasmasphere and an extended plasmaspheric 'tail'.

Although defining the transient response of the plasmasphere to changing geophysical conditions continue to require robust studies like that of *Carpenter et al.*, [1992] or the use of innovative remote, global imaging [*Williams et al.*, 1992; *Garrido et al.*, 1994; *Frank et al.*, 1994], the azimuthal profile of the plasmasphere under stable geophysical conditions can be suggested by combining existing observational studies. The following analysis is based on the results of studies by *Higel and Wu* [1984], *Carpenter and Anderson* [1992], and *Moldwin et al.*, [1993]. The works by both *Higel and Wu*, [1984] and *Moldwin et al.*, [1993] are based on observations from geosynchronous orbit (L=6.6). These researchers establish criteria for defining encounters with plasmaspheric plasma and then proceed to statistically quantify the local time width and the centroid of the plasmasphere as a function of geomagnetic activity. *Carpenter and Anderson*, [1991], using both ISEE 1 upper hybrid wave and ground whistler measurements, study the plasmapause between 0 hours and 15 hours magnetic local time, and find it to be statistically symmetric in this local time range. They also quantify the change of the plasmapause location in L-shell as a function of geomagnetic activity. A result of combining these observations is presented below. The implications and limitations of the result are then discussed. The objective is to develop an empirically-based description of the azimuthal plasmapause profile under steady geophysical conditions. These results should be useful for empirical modeling of the inner magnetosphere and should serve as a basis for understanding the response of the plasmasphere to changing geophysical conditions.

Observations of the Azimuthal Plasmapause Profile

Carpenter and Anderson [1991] based their determination of the plasmapause location on measurements from the Plasma Wave Instrument on the ISEE 1 spacecraft. Electron density was determined at magnetic latitudes less than 30 degrees and between 0 hours and 15 hours magnetic local time. Only those plasmapause profiles for which the number density dropped by a factor of 5 or more over a distance of $\Delta L <= 0.5$ were used. When multiple plasmapause features were found, only the inner most plasmapause was used. A least squares linear fit was performed between the L value of the plasmapause (L_{pp}) and the maximum K_p (K_{pmax}) measured in the preceding 24 hours, resulting in the relation

$$L_{pp} = 5.6 - 0.46 K_{pmax} \, . \qquad (1)$$

The preceding one, two, or three values of the 3-hour K_p average were ignored for those plasmapause measurements made in magnetic local time intervals centered at 9, 12, and 15 hour local times, respectively. No significant variation in Lpp was found with local time between 0-15 hours MLT.

Higel and Wu [1984] used the Relaxation Sounder experiment on the GEOS 2 spacecraft to obtain total density at geosynchronous orbit. Sharp positive and negative density gradients were used to define entry and exit out of the plasmasphere. It was required that the density jump by a relative factor of 2 over three consecutive 12-min spaced samples for a plasmapause to be identified. Density variations from 1 cm^{-3} per min to several tens of cm^{-3} per min were observed.

The average MLT between the entry and exit out of the plasmasphere was defined to be the local time centroid (Φ) of the plasmasphere extension to geosynchronous orbit. A strong correlation was found between phi and the average K_p for the preceding 9-hours ($K_{p}9$).

$$\Phi(\text{hours}) = 23.45 - 1.92K_{p}9 \qquad (2)$$

A similar strong linear correlation was found between the local time width ($\Delta\Phi$) of the plasmasphere at geosynchronous orbit and K_p. In this case, measurements were restricted to times of relatively steady geomagnetic conditions (K_p) over the preceding 24 hours.

$$\Delta\Phi(\text{hours}) = 5.41 - 1.05K_p \qquad (3)$$

A similar study was performed by *Moldwin et al.* [1993] using the Magnetospheric Plasma Analyzers on board two geosynchronous satellites, 1989-046 and 1990-095. Measured three dimensional ion distributions were integrated to obtain number density with a time resolution of 86 seconds. Average K_p ($\overline{K}_p$) over the preceding 12-hour intervals was related to the local time of the observed plasmaspheric bulge mid-point and bulge local time width. Only those events following steady K_p levels were included. A threshold density of 10 cm^{-3} was used to identify the plasmasphere. Multiple plasmaspheric encounters were recorded whenever observed densities fell below this threshold for more than 15 min. A linear fit was performed for the bulge local time and for $\overline{K}_p > 2$.

$$\Phi(\text{hours}) = 19.5 - 0.52\,\overline{K}_p \qquad (4)$$

At a level of geomagnetic activity of $K_p = 2$ and below, the plasmaspheric plasma was observed at essentially all local times, therefore no relationship with K_p could be established.

The width of the plasmaspheric bulge at geosynchronous orbit was found to take on any value up to a maximum as a function of $\overline{K}_p$. That maximum is defined by the expression

$$\Delta\Phi(\text{hours}) = \frac{17.2}{\overline{K}_p} \ . \qquad (5)$$

Moldwin et al. report that the primary difference between this result and that of Higel and Wu is for $\overline{K}_p > 2$, although they find bulge widths both more narrow and wider than those found by Higel and Wu at all levels of geomagnetic activity. The significant difference in sampling rates (one sample every 12 min versus one every 86 seconds) may have prevented Higel and Wu from seeing the short time scale structure observed by Moldwin et al. at low K_p levels. The longer sampling time of Higel and Wu would result in an effective averaging over the small scale features observable by Moldwin et al. The consequence will be a smoothing of densities that may lead to measurements that fail to be identified as plasmaspheric encounters by Higel and Wu.

A Composite Picture of the Plasmapause Profile

If these works can be related, the opportunity exists to obtain a rough picture of the azimuthal profile of the plasmapause. Carpenter and Anderson provide a measure of the radial variation of the plasmapause with changing geophysical conditions. The other papers obtain local time measures of the location and width of the plasmasphere at geosynchronous orbit. Taken together, these works are used here to derive an expression for the azimuthal plasmapause profile, which has implications for convection electric field models and which may be less sensitive to the usual time-aliased, statistical averages of plasmapause location based on observation. Needed assumptions will be stated as we proceed. The implications of those assumptions and the limitations of this approach are discussed in the next section.

We first assume that the radial plasmapause variation defined in Equation 1, for magnetic local times from 0 hours to 15 hours under changing geophysical conditions (as given by K_p), also defines the proportional change in the plasmapause across remaining local times, i.e. from 15 to 24 hours. The plasmapause L-shell at all local times can then be represented by the following equation

$$L_{pp}=(5.6 - 0.46K_p)(1+f(x)), \qquad (6)$$

where the first term is Equation 1 from Carpenter and Anderson and f(x) is a function that represents the deviation of the plasmapause from a circular profile as a function of local time. The variable x will be used to measure local time relative to the centroid of the bulge. Although there is evidence that the bulge region may not be symmetric about the centroid [e.g., *Carpenter et al.*, 1992], we will assume symmetry for this exercise. To this point, f(x) is a symmetric function of x, but otherwise remains to be defined. Circular, semi-circular, and tear-drop profiles for the equatorial plasmaspause can all be represented by Equation 6. In the derivation of f(x) that follows, we also assume that the form of this function is independent of the level of geomagnetic activity (K_p).

Both Higel and Wu and Moldwin et al. determine a bulge width that decreases with increasing geomagnetic activity. In the case of Moldwin et al., the bulge width is found to vary between small values and the upper bound given Equation 5. Higel and Wu, however, find a more ordered, less variable, trend given by Equation 3. As discussed above, the differences between these results may be that the maximum bulge width identified by Moldwin et al. includes small scale plasmaspheric density structures in addition to the general profile. Structures near the plasmapause are frequently seen and may result from surface waves or from continually changing geophysical conditions, which lead to the formation of density irregularities both inside and outside the nominal plasmapause location. The much shorter sample time in the Moldwin et al. study may result in their greater ability to see these structures, especially at low levels of geophysical activity when the plasmasphere expands toward L = 6.6. However, the general trend is the same, i.e. the width decreases with increasing K_p. The objective of this study is to focus on the steady state azimuthal profile of the plasmapause, rather than the structures which arise from changing conditions. With this and the longer steady state conditions required by Higel and Wu for their observations in mind (24 hours rather than 12 hours), their description for bulge width will be used here.

The bulge width given in Equation 3 is related to Equation 6 by noting that the plasmapause will be at $L_{pp} = 6.6$ at an azimuth relative to the centroid (x) which is half of the bulge width given in Equation 3 or when

$$x = \frac{5.41 - 1.05K_p}{2} \qquad (7)$$

Letting $L_{pp} = 6.6$ in Equation 6 and solving for f(x), we can determine a set of corresponding f(x) and x values as a function of K_p. With this set of values, a functional relationship can be determined between f(x) and x. Such a set of values is plotted in Figure 1 (solid line), along with a least squares fit of an exponential function of a polynomial which is third order in x (dotted line).

$$f(x) = e^{(-0.03x^3+0.05x^2-0.57x+0.05)} \qquad (8)$$

The values for f(x) and x, in Figure 1, are limited to x just under 3 hours, because this corresponds to the maximum plasmaspheric width seen by Higel and Wu at geosynchronous orbit. The exponential form of Equation 8 insures that the azimuthal profile reduces smoothly to the constant circular profile of Carpenter and Anderson for values of x larger than 3 hours. Equation 8 is derived for K_p values ranging from 0 to about 5. Levels of geophysical activity corresponding to K_p greater than 5 do not contribute to Equation 8, because the plasmasphere cannot be seen at geosynchronous orbit during such high levels of activity. The resulting profiles for the plasmapause for $K_p = 1, 3, 5$, and 7 are shown in Figure 2 as solid lines. Although now necessarily unique, these plasmapause profiles are consistent with the plasmapause measurements of Carpenter and Anderson, Higel and Wu, and Moldwin et al.

Plasmapause profiles are shown in Figure 2 relative to the bulge centroid (x = 0 hours) and without specific orientation of the bulge relative to the Earth-Sun line. However, both Moldwin et al. and Higel and Wu report a local time for the bulge centroid which depends on geomagnetic activity. Although Moldwin's observations of the local time of the bulge centroid are scattered for low K_p, they become less ambiguous for $\overline{K}_p > 3.5$ and strongly suggest that the bulge does not rotate to a position earlier than about 15 hours MLT. Higel and Wu observations are less ambiguous at lower K_p values, perhaps due to their lesser sensitivity to small density features, as mentioned earlier. The larger number of observations in the Moldwin et al. study suggest a more statistically accurate measure of the bulge location for larger Kp values, while the greater sensitivity to small scale, possibly transient, features makes the Moldwin et al. study more difficult to use at lower K_p values. One approach is to make use of Moldwin et al.'s results at high K_p and that of Higel and Wu at low K_p. Figure 3 shows plots of bulge centroid versus K_p from these two studies (solid lines) and a curve fit (dashed line), following this approach,

$$\Phi = \frac{47}{K_p + 3.9} + 11.3 \,. \qquad (9)$$

This functional relation approximates the Moldwin et al. result at high K_p and the Higel and Wu result at low K_p. The constants in Equation 9 were derived using a least-squares technique, but have been rounded and, in the case of the leading constant, slightly reduced to prevent the fitted function from giving a bulge location in local time that is later than the Higel and Wu result at $K_p = 0$. The application of this result to Equations 6 and 8 is presented in Figure 4, which shows an extended plasmasphere that shrinks and rotates sunward with increasing K_p.

Discussion

A tear-drop like azimuthal profile for equatorial, high density plasmaspheric plasmas has resulted from combining the observations of *Higel and Wu* [1984], *Carpenter and Anderson* [1992], and *Moldwin et al.* [1993]. What does this profile represent? Under what conditions is this picture valid?

One issue is the degree to which the results of these three studies can be directly compared, when Carpenter and Anderson make use of the maximum K_p in the preceding 24 hours (with the limitations noted above), while Higel and Wu and Moldwin et al. use the average K_p during intervals of steady geophysical activity of 24 hours and 12 hours, respectively. The maximum K_p used by Carpenter and Anderson corresponds to the maximum erosion of the plasmasphere as a result of recent geophysical activity [*Horwitz et al.*, 1990], where the erosion process takes place on a time scale of one day or less [*Park*, 1974]. It can be expected that the innermost plasmapause boundary identified by Carpenter and Anderson would also correspond to the location of the plasmapause, had the level of geophysical activity been held steady indefinitely at the maximum corresponding to each measurement. Under prolonged steady conditions, it is expected that the plasmapause and the separatrix between corotational and convective motions would be the same.

The other two studies identify the outermost plasmapause feature measured at geosynchronous orbit following approximately a half day of steady geophysical conditions. Using whistler observations, *Park* [1974] determined the time required to refill evacuated flux tubes to saturated density levels to be approximately 1 day for L = 2.5 and 8 days for L = 4. What would eventually become the plasmapause following prolonged steady geophysical conditions, however, will be measurable on much shorter time scales as flux tube filling proceeds [see review by *Singh and Horwitz*, 1992]. The outermost plasmapause boundary identified by *Higel and Wu* and by *Moldwin et al.* is likely to correspond to the developing plasmapause resulting from recent steady conditions. This is the same plasmapause, i.e. separatrix, which would be found under saturated conditions were geophysical activity to remain constant much longer. In this way, these three studies consistently identify comparable plasmapause locations and corresponding geophysical conditions, as represented by K_p.

This determination depends upon the opportunity for a geosynchronous orbiting spacecraft to measure a forming plasmapause after 12 hours to 24 hours of steady geophysical activity. If refilling is characterized by an outward propagating plasmapause, as a result of inner L-shells filling quicker than outer L-shells [*Park*, 1974], then many days might be required before significant evidence of refilling becomes available at geosynchronous orbit. If refilling proceeds over a range of corotating L-shells, a density shelf might appear [*Carpenter and Park*, 1973;

Horwitz et al, 1984] and be measurable at geosynchronous orbit after only a short period of steady conditions. A simple demonstration of refilling can be made by following the approach of *Rasmussen et al.* [1993], where diurnally averaged filling on a given flux tube is found to approximately follow an exponential asymptotic dependence (see their Figure 4):

$$n(t) = n_o\left(1 - e^{-t/t_a}\right), \qquad (10)$$

where n_o is the saturation density, t is time, and t_a is the time constant for refilling. The time constant across a range of L-shells for refilling can be estimated from *Park* [1974], by assuming that refilling is at least 90% complete (more than 2e-foldings) after 8 days at L = 4 and linearly scaling to other L-shells by flux tube volume. A dipole field is used for simplicity. A level of 90% is chosen, because a level of 100% is mathematically impractical with exponential filling and because a 90% level of filling will be observationally indistinguishable from fully saturated density levels. The density levels associated with saturated and "empty" flux tubes can be taken from *Carpenter and Anderson* [1991]. At midnight (local time chosen for demonstration purposes only), they find plasmaspheric saturation densities to be given approximately by

$$n_e = 10^{(-0.3145L+3.9043)}. \qquad (11)$$

Minimum density levels in the trough are approximated by

$$n_e = 5800L^{-4.5} + \left(1 - e^{\frac{-(L-2)}{10}}\right). \qquad (12)$$

The demonstration can be completed by further assuming that the initial (t = 0) plasmapause corresponds to that given by *Carpenter and Anderson*, [1991] for $K_p = 5$. This places the plasmapause initially at a low L-shell so that filling in outer L-shells can be seen. Other than this consideration, there is nothing special about this value of K_p. The initial ($t = 0$) plasmasphere and trough density profile is shown in Figure 5 as a solid line. The dashed lines show the state of outer L-shell refilling after 3, 6, 9, and 12 hours and after 1, 2, 3, and 4 days. It is evident in Figure 5 that the plasmapause defined for $K_p = 5$ remains observable at least one day following the onset of refilling. Refilling proceeds at higher L-shells such that a plateau develops like that seen by *Corcuff et al.* [1972] and *Horwitz et al.* [1994]. The refilling in Figure 5 is also similar to the theoretical results of *Khazanov et al.* [1984]. *Rasmussen et al.* [1993] note that a numerical, first-principles model by *Guiter et al.* [1991] shows diurnal increases above his simple filling model as flux tubes are carried to the dayside, then later falling back to the simple model at midnight. The densities anticipated at afternoon and evening local times, therefore, will be somewhat larger than that shown here. Figure 5 is, therefore, reasonably consistent with an observable plasmapause feature at geosynchronous orbit after a half day of steady geophysical conditions.

The profiles resulting from the combination of these three studies are show in Figures 2 and 4. Also shown in Figure 2 is a dashed line tracing the separatrix between corotational and convective flows that results from a simple constant cross-tail electric field (for $Kp = 1$) added to the corotational electric field [*Roederer*, 1970; *Lyons and Williams*, 1984],

$$L_{pp}\sqrt{\frac{c_1}{c_2}\frac{\sqrt{\sin\Phi+1}}{\sin\Phi}}-1 \qquad (13)$$

where $c_1 = 91.5$ ke VR_E and c_2 has the same units and is chosen such that the stagnation point in the convection model coincides with our bulge centroid. At first glance, the derived plasmapause profile is remarkably similar to that obtained from the simple convection model of Equation 10. Closer examination reveals that these profiles may be observationally distinguishable. The Carpenter and Anderson location for the plasmapause opposite the bulge would need to be in error by nearly 20% or the Higel and Wu bulge width would need to be in error by nearly 60% before the plasmapause profile derived here could be considered consistent with a simple convection model. In Carpenter and Anderson's determination of the plasmapause location (see their Figure 6) there are limited statistics at low K_p and significant scatter at higher K_p values. Their measurements of the plasmapause position (L_{pp}) at low K_p also suggest possible higher values than that given by the fitted line, rather than a lower value which would be required to match our derived plasmapause profile with that of the simple convective model.

By changing the value of the parameter c_2 in Equation 10, it is possible to match the simple convection model to our derived profile on the side opposite the bulge, rather than at the stagnation point. The derived bulge width and extension in radial distance, however, does not match that for the simple convection profile. Higel and Wu have limited statistics at low values of K_p for determining bulge width, which cannot preclude a wider bulge profile. An error of almost 60% is required in the Higel and Wu bulge width determination before the derived bulge profile would be consistent with the simple convection model. The Moldwin et al. study finds bulge widths smaller and larger than those of Higel and Wu, however, it is unable to provide a clear determination of the bulge width due to the wide scatter in observed widths. The maximum bulge widths derived by Moldwin et al. for various values of K_p are considerably larger than those found for the simple convection model. Therefore, although there is significant similarity between the derived plasmapause azimuthal profile and that obtained from a simple convection model, the similarity may be only superficial.

To obtain correspondence between the plasmapause profiles from simple convection and from this study for $K_p = 1$ (see Figure 2), a modification of the simple convection model is required. At local times opposite the bulge, the influence of the corotational electric field must be extended to somewhat larger L-shell, like that which would result from dielectric shielding. At larger L-shells an enhancement of the convection electric field over the corotational field may result in a narrowing of convection streamlines at bulge local times. In both L-shell regions, a relatively simple modification of the simple convection model is suggested. That modification is accomplished by assuming that a radially dependent multiplicative factor on the electric potential due to simple convection can be derived so as to match the convection separatrix with the derived plasmapause profile in Figure 2. The total electric potential can then be given as

$$\Phi = -\frac{c_1}{r} + c(r) r \sin\Theta \ , \qquad (14)$$

where the constants c_1 and c_2 from the simple convection model [*Roederer*, 1970; *Lyons and Williams*, 1984] and c_2 has been replaced by c(r). A rough correspondence between this convection electric field model and our derived plasmapause profile ($K_p = 1$) can be obtained for

$$c(r) = 1.092\left(0.7 - e^{-\frac{r^{3.5}}{440}}\right) . \qquad (15)$$

Equation 15 is graphed in Figure 6. What is found is characteristic of a charge separation layer, centered near L = 5. L = 5 is also the approximate L-shell of the plasmapause away from the bulge for $K_p = 1$. The implication is that the externally imposed convection electric field results in a global, radially dependent, charge separation that shields the inner magnetosphere. The resulting picture of convection/corotation streamlines, along with our derived plasmapause profile (heavy line) for $K_p = 1$, and including our modeled bulge rotation is shown in Figure 7. Similar empirical convection models can be obtained for other levels of geomagnetic activity, but this will be left for a subsequent report.

Our understanding of the transport of plasma away from the plasmasphere and of the formation of a new plasmapause remains incomplete. The observed disappearance of plasma from the plasmasphere, for example, may occur without requiring plasma to be transported to and lost at the magnetopause. *Khazanov et al.* [1994] offer an alternative explanation for the observed low densities in the outer magnetosphere. It is shown by Khazanov et al. that flux tubes convected away from the plasmasphere will reach a state of plasma redistribution in the enlarged flux tube on a time scale faster than that required for filling to occur from the ionosphere. The result is a rapid drop in flux tube density as plasma is convected away from the Earth and the apparent evacuation of convecting flux tubes. This analytical work, however, appears inconsistent with observations by *Carpenter et al.* [1993] of long lasting enhanced density structures outside the plasmasphere. *Carpenter et al.* [1993] find plasmaspheric-like density structures outside the plasmasphere following a substorm and subsequent period of quiet geomagnetic conditions. One possible explanation is that plasma convected away from the plasmasphere and toward the magnetopause is not entirely lost at that boundary to the solar wind. If some magnetic field lines initially convected toward the magnetopause are later turned inside of the magnetopause toward the magnetospheric flanks and convected tailward, continued ionospheric outflow may add to entrained plasmaspheric plasma and lead to enhanced densities over that otherwise observed in the trough. Tailward convection along the magnetospheric flanks from the vicinity of the dayside magnetopause would not result in a continued expansion of flux tube volume and commensurate drop in density, like that which may occur as plasma is originally convected away from the plasmasphere [*Khazanov ta al.*, 1994]. As demonstrated in Figure 5, significant filling can occur should such flux tubes linger near the Earth for periods of one half day or more.

Moldwin et al. also see considerable plasmaspheric structure at geosynchronous orbit, especially for quiet geophysical conditions. As discussed earlier, the scatter seen by Moldwin et al. in locating the centroid of the bulge for K_p<2 relative to the results of Higel and Wu may be due to their greater temporal resolution and selection criteria for defining plasmaspheric intervals. The structures seen in the Moldwin et al study at low K_p may be related to waves or other density structures often seen in the vicinity of the plasmapause [*Carpenter and Anderson,* 1991; *Carpenter et al.*, 1992, 1993; *McComas et al.*, 1993]. At $K_p = 2$ for example, Equation 1 (obtained from *Carpenter and Anderson*) gives a plasmapause radius of almost 5 R_E for local times away from the bulge region. The possibility exists that considerable structure remains in the vicinity of the plasmapause following a return to quiet geophysical conditions. *Lemaire and Kowalkowski* [1981] report that several days may be required for the velocity interchange mechanism to reach a steady state. As a result, the 12 hours of required steady conditions in the Moldwin et al. study may not be sufficient to avoid encountering residual density structures from previous geomagnetic activity.

It is important to emphasize that the plasmapause shown in Figure 4 is expected to represent steady state, but not a common state of the plasmasphere. Temporal changes in convective electric fields do not immediately change the distribution of plasmaspheric plasmas. Time is required for the filling of previously emptied flux tubes and for the transport of filled flux tubes to the dayside magnetopause where that plasma is presumably lost [*Park*, 1974]. Figure 4 is intended to suggest the equatorial, azimuthal profile of the plasmasphere under steady state conditions and at various levels of geomagnetic activity. Even though this picture of the azimuthal profile of the plasmapause may only be seen after a long period of steady geophysical conditions, it can serve as a guide to understanding the factors which influence the accumulation and loss of plasma in the inner magnetosphere. In particular, the azimuthal profile for the plasmapause obtained in this study may be used as evidence of the morphology of corotational and convective electric fields under steady geophysical conditions, as demonstrated above.

The well-known reduction in size of the plasmasphere with increasing convection combines with the rotation of the bulge region detailed in this work to produce a very large change in the plasma environment in the evening local time sector where substorm injection processes are active, as activity increases. As pointed out by *Moore et al.* [1987], large changes of plasma density also produce large changes in the topography of the index of refraction for magnetohydrodynamic waves, with potential impacts on the nature of transient phenomena with time-scales on the order of the wave transit time. In particular, the density gradient of the plasmapause corresponds to an opposite gradient in the fast mode propagation speed.

Conclusions

The results derived above imply strongly that the magnetospheric circulation flow field (and its associated electric field) depart significantly from the simple model of a uniform sunward flow. The gross shape of the convection boundary or plasmapause has a slightly lesser azimuthal amplitude than for uniform sunward flow. This indicates that the flow has a dependence on radius with respect to the Earth, with weaker flow near the Earth, consistent with some electrostatic shielding of the convection electric field. The detailed shape of the plasmapause should reflect the functional dependence of the electrostatically shielded electric field. However, strong shielding would render the plasmapause in a nearly circular shape, so the shielding is rather subtle compared with the limiting possibilities.

Perhaps more significant is the rotation of the plasmapause shape with increasing Kp. This implies a corresponding rotation of the magnetospheric circulation flow direction, from duskward at low activity to dawnward at higher activity levels when the flow is stronger. We are unaware of any theoretical predictions concerning such a rotation, but it seems suggestive of a coherent change in the nature of the magnetospheric wake as convection intensifies.

In summary, available studies of the plasmapause region from spacecraft operating in different distance ranges from the Earth can be straightforwardly synthesized into a description of the azimuthal shape of the plasmapause and convection boundary. The shape so derived is reminiscent of that which has been long-associated with the convection boundary in a simple model of sunward flow and corotation, but with very significant differences. There is a subtle but observable difference in the detailed shape bearing evidence of some electrostatic shielding, and a more significant gross rotation of the plasmaspheric bulge with increasing activity, that removes the bulge from the evening region of energetic plasma injections.

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FIGURE CAPTIONS

Figure 1. The profile of the bulge (f(x) is derived as a function of the azimuthal rotation from the bulge centroid (x). the function f(x) is based on bulge observations from geosynchronous orbit over a range of geomagnetic conditions (dots are shown every $\Delta K_p = 0.5$).

Figure 2. Profiles of the plasmapause (solid lines) for levels of geomagnetic activity corresponding to $K_p = 1, 3, 5$, and 7 are shown relative to the bulge centroid (x = 0 hours). The separatrix between convective and corotational flows (dotted line) for a simple, constant cross tail electric field ($K_p = 1$) is also shown.

Figure 3. A least squares fit for the magnetic local time location of the bulge centroid (dotted line) as a function of K_p is shown along with the bulge centroid determinations of *Higel and Wu* [1984] and Moldwin et al. [1993}.

Figure 4. Derived profiles for the steady state plasmapuase at four levels of geomagnetic activity corresponding to $K_p = 1, 3, 5$, and 7.

Figure 5. Estimated daily average profiles for refilling at midnight following a maximum level of geomagnetic activity if $K_p = 5$ and periods of quiet activity of 3, 6, 9, and 12 hours and of 1, 2, 3, and 4 days.

Figure 6. A multipicative factor for the potential corresponding to a constant cross tail electric field is hown. This factor results from a modification of the simple convection model in order to approximate the empirically derived plasmapause profile at $K_p = 1$.

Figure 7. Tthe streamlines for corrotational and convective flaws resulting from the modified convection model at $K_p = 1$ are shown. Also shown (heavy line) is the corresponding empirically derived plasmapause profile. The bulge centroid is rotated to near 21 hours MLT.

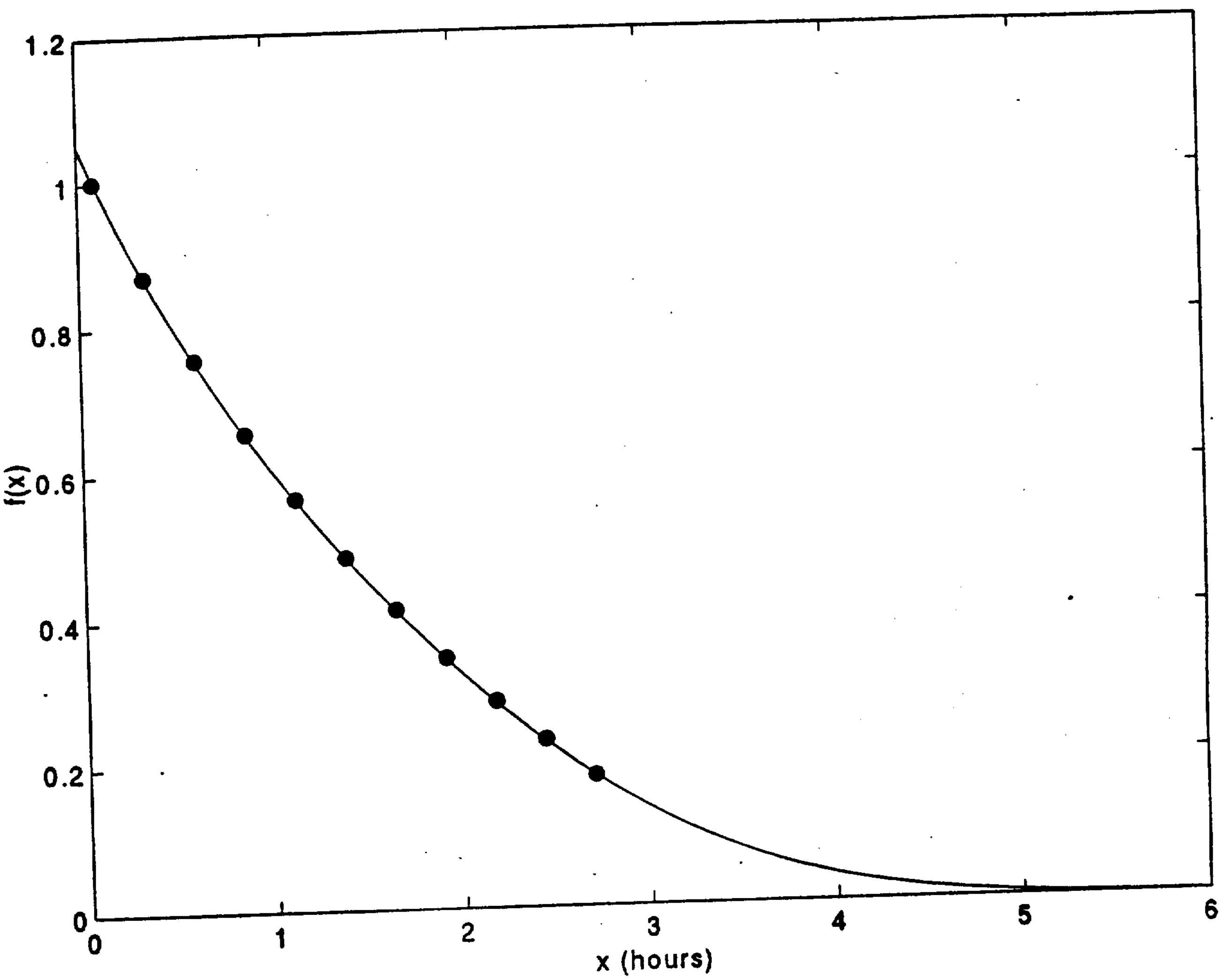
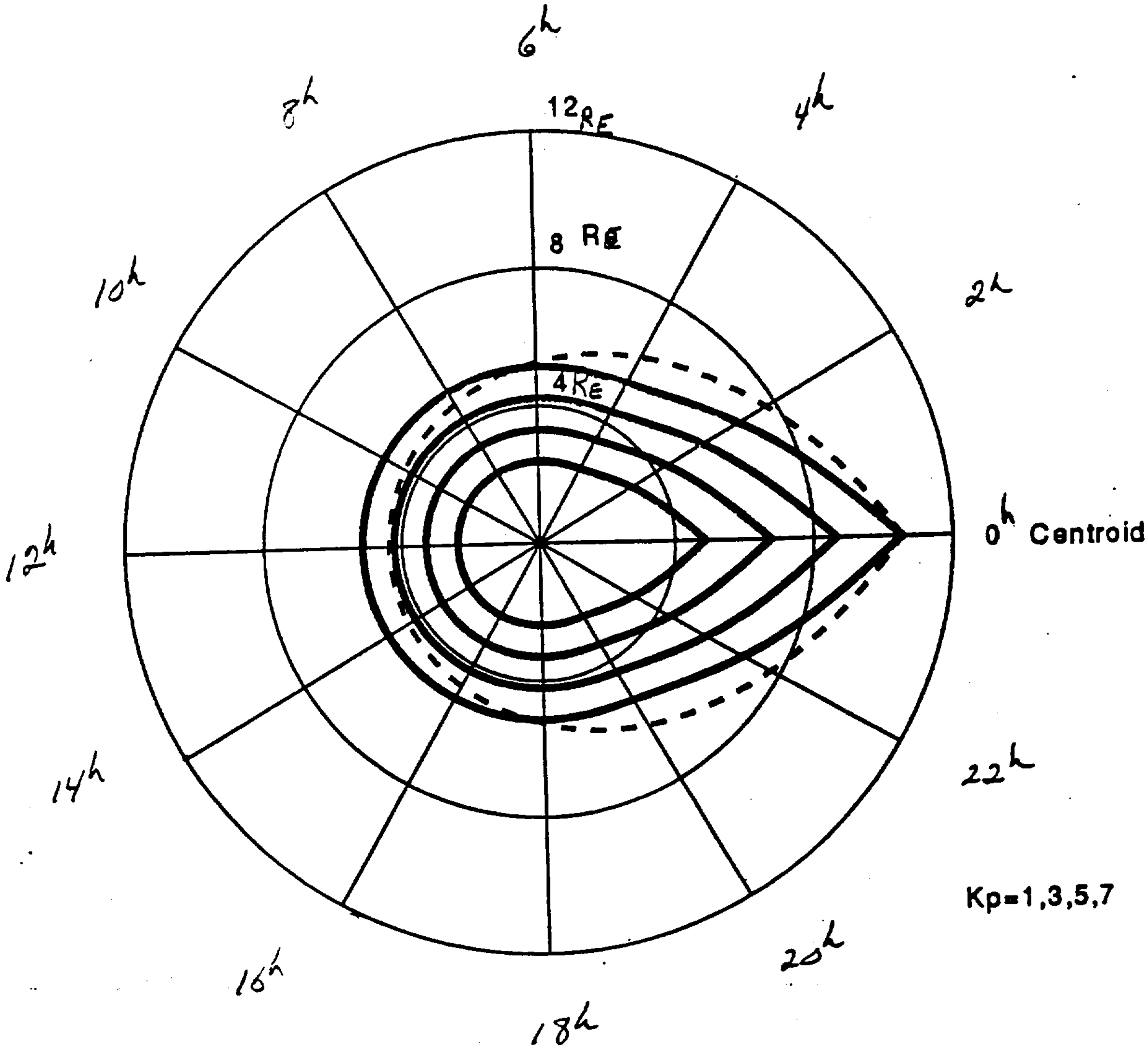


Figure 1



6h
12 RE
4h
8h
8 RE
10h
2h
4 RE
12h
0h Centroid
14h
22h
Kp=1,3,5,7
16h
20h
18h

Figure 2

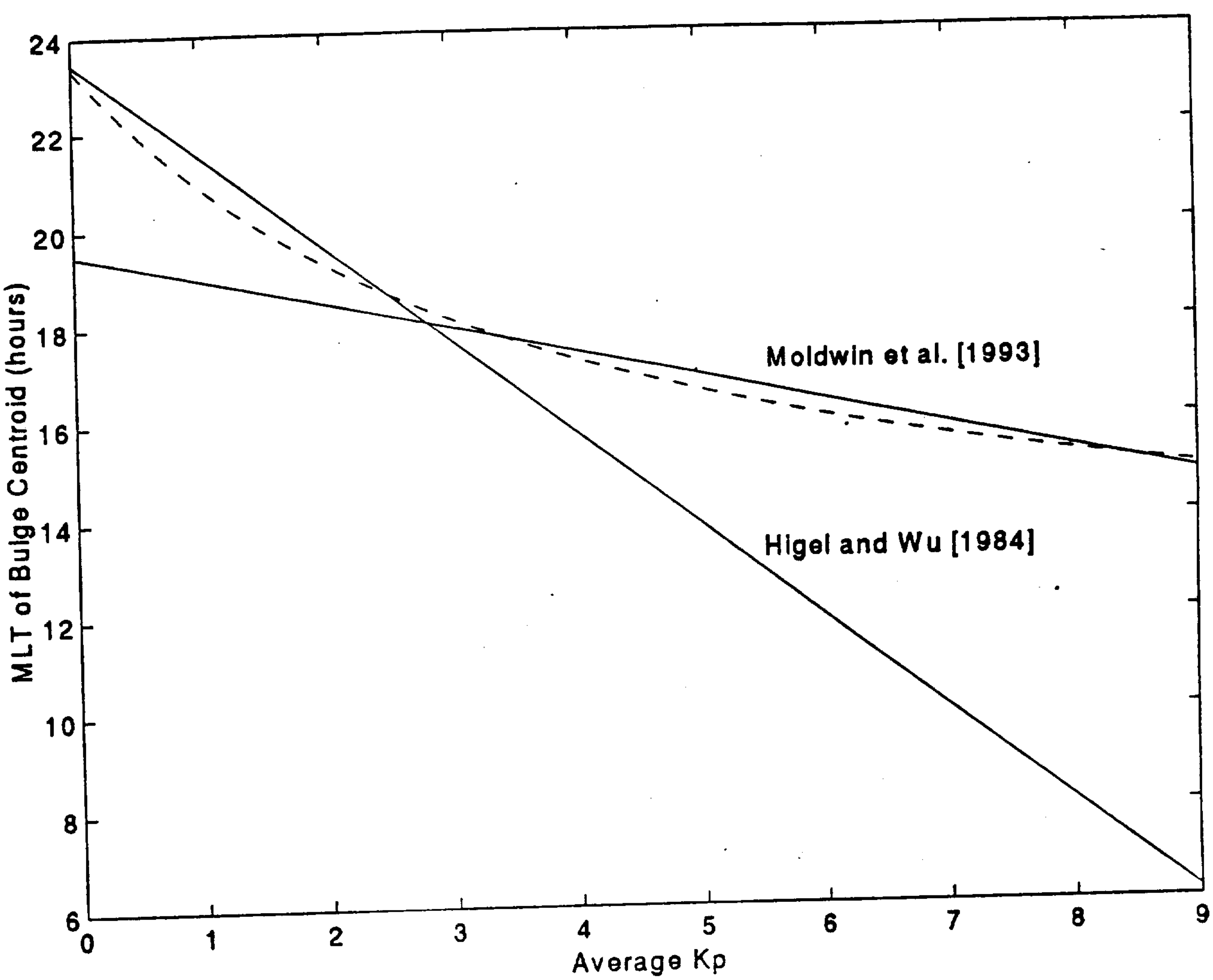

24
22
20
18
16
14
12
10
8
6
MLT of Bulge Centroid (hours)
0
1
2
3
4
5
6
7
8
9
Average Kp
Moldwin et al. [1993]
Higel and Wu [1984]

Figure 3

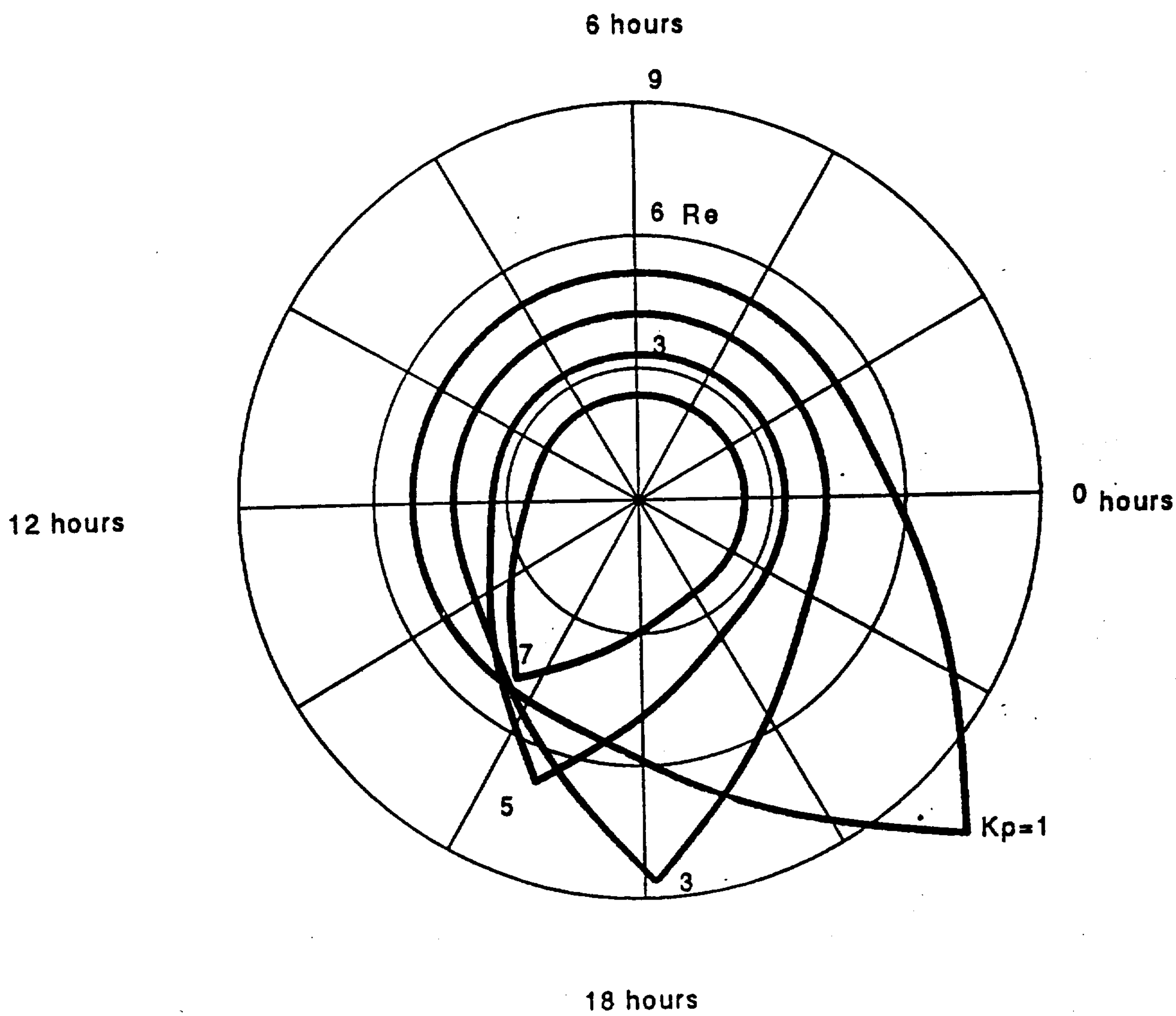
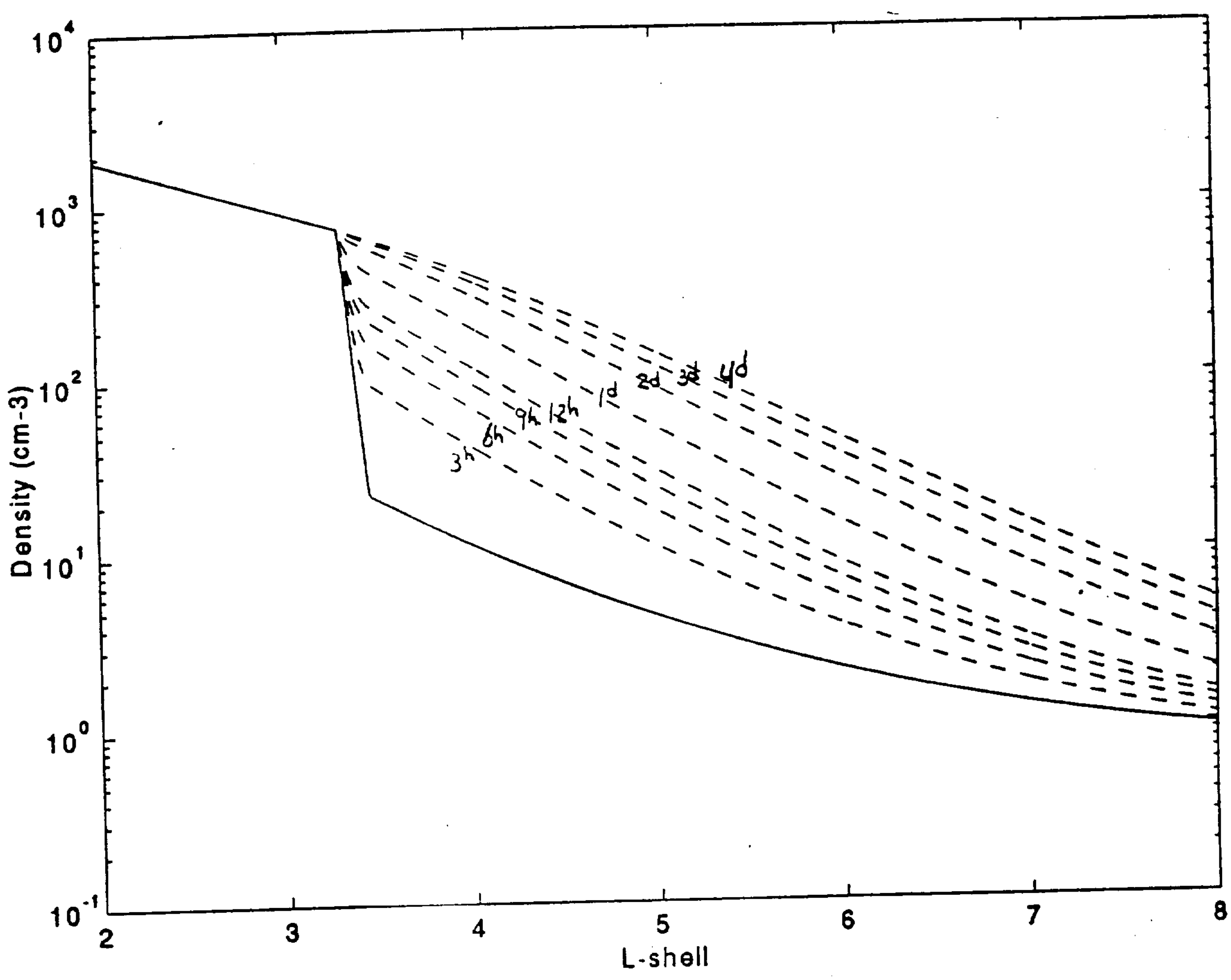
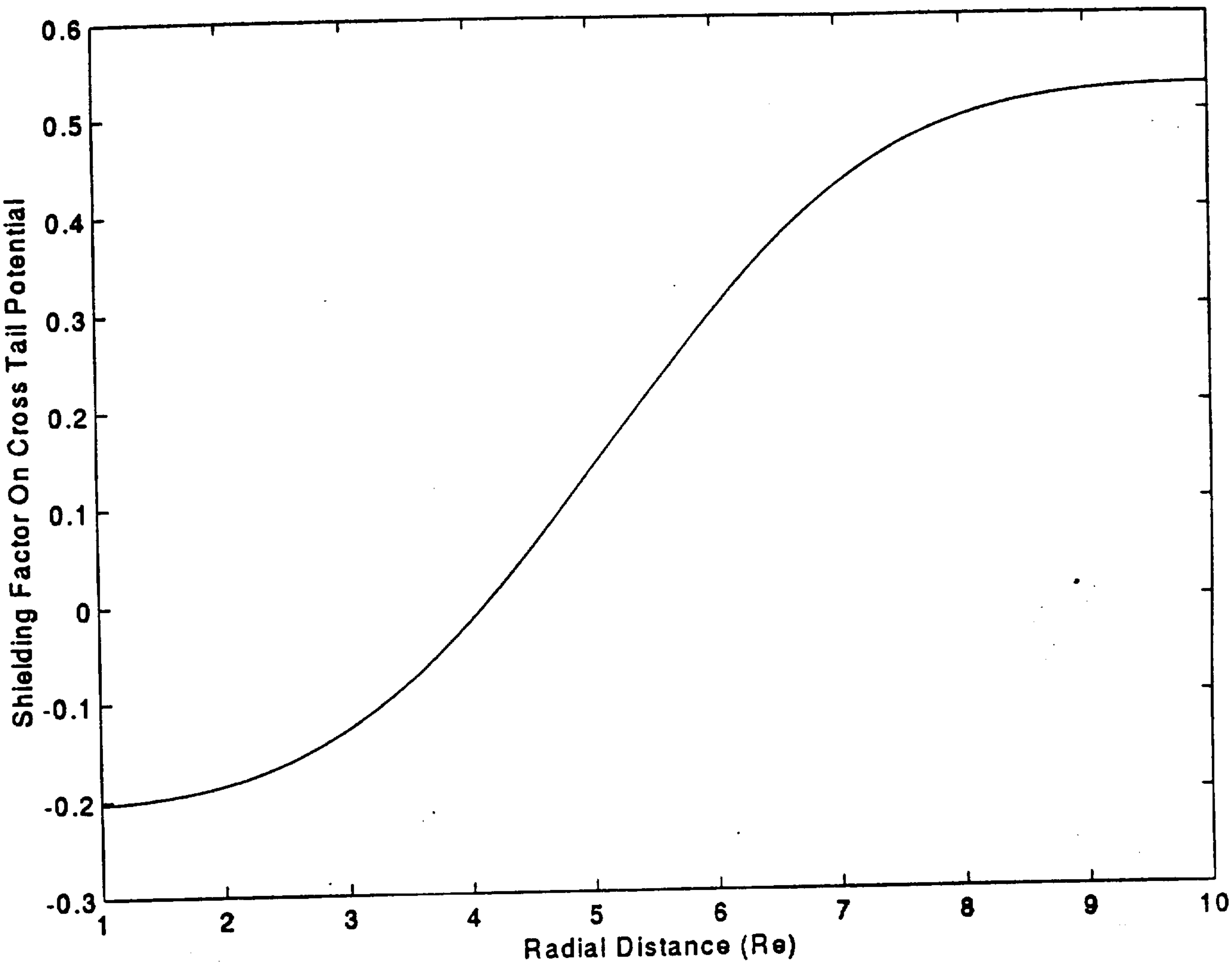


Figure 4



10^4
10^3
10^2
10^1
10^0
10^-1
Density (cm-3)
2
3
4
5
6
7
8
L-shell
3h
6h
9h
12h
1d
2d
3d
4d

Figure 5



0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Shielding Factor On Cross Tail Potential
1
2
3
4
5
6
7
8
9
10
Radial Distance (Re)

Figure 6

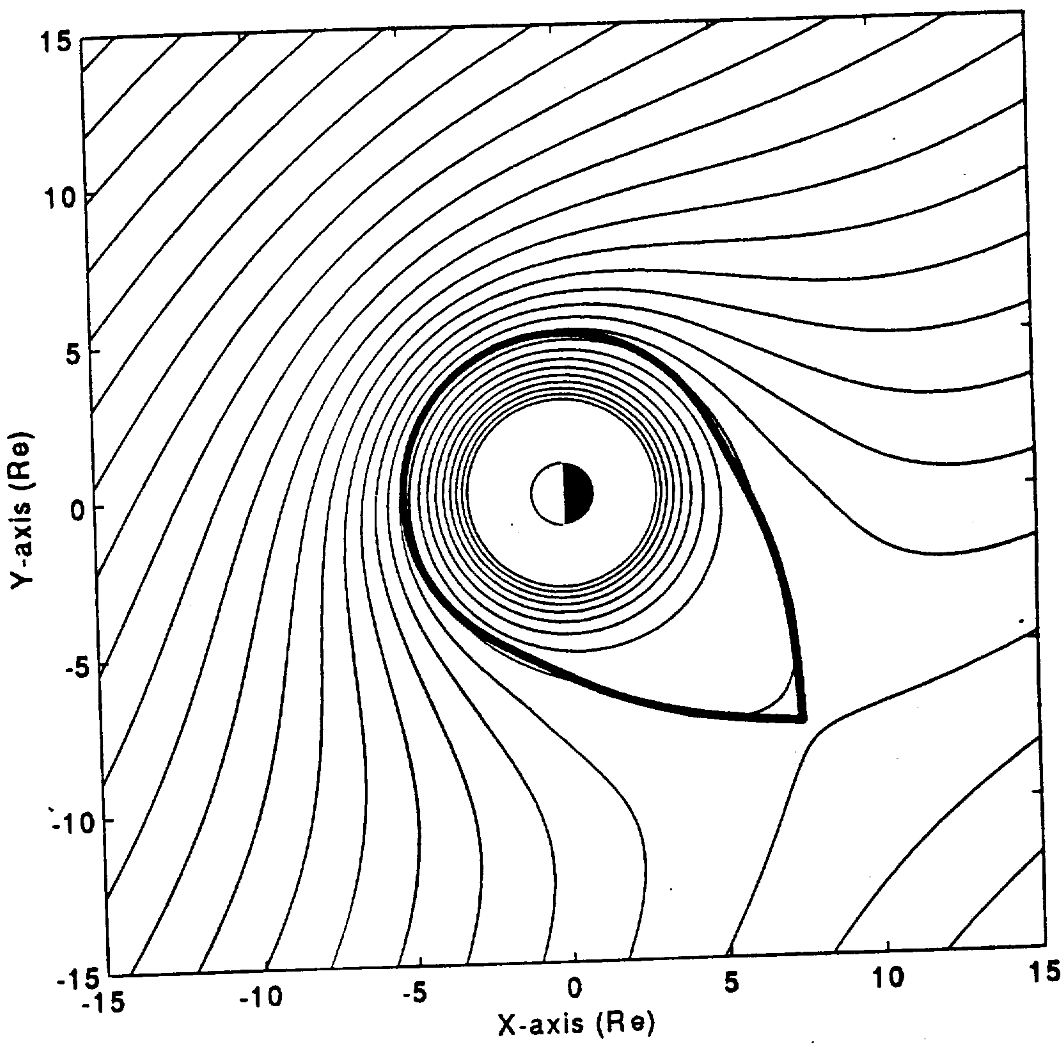


Figure 7